System Performance Assessment for Magnetohydrodynamic Energy Generation During Planetary Entry

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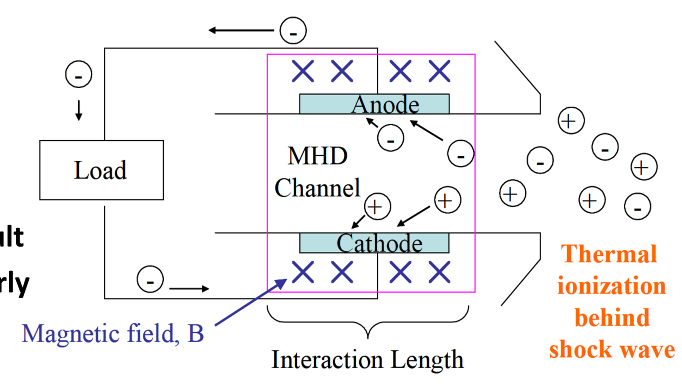
Introduction and Motivation

Abstract

Proposed missions such as a Mars sample return mission and a human mission to Mars require landed payload masses in excess of any previous Mars mission. Whether human or robotic, these missions present numerous engineering challenges due to their increased mass and complexity. To overcome these challenges, new technologies must be developed, and existing technologies advanced. Mass reducing technologies are particularly critical in this effort. The proposed work aims to study the suitability of various entry trajectories for reclaiming vehicle kinetic energy through magnetohydrodynamic energy generation from the high temperature entry plasma. Potential mission and power storage configurations are explored, with results including recommended trajectories, amount of kinetic energy reclaimed, and additional system mass for various energy storage technologies.

Motivation: Mars Entry, Descent, and Landing (EDL)

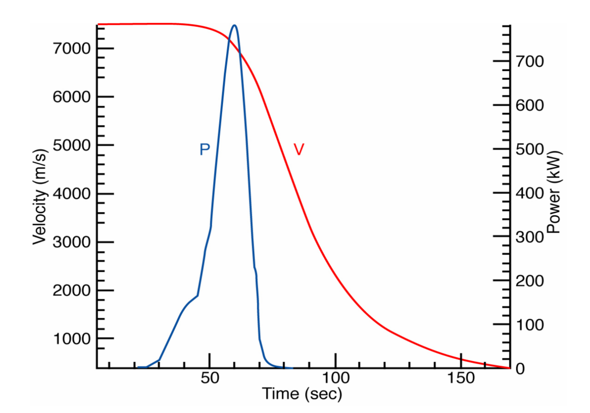
- Reduce velocity from interplanetary trajectory velocity to zero
- Requires large kinetic energy change, usually through atmospheric drag
- Relatively thin Martian atmosphere limits drag
- High mass Mars landings prove difficult
- Mass reducing technologies particularly beneficial
- What if this dissipated kinetic energy could be harnessed?



Schematic of a Magnetohydrodynamic Energy Generator[3]

Magnetohydrodynamic (MHD) Energy Generation During EDL

- Rapid atmospheric deceleration at hypersonic speed causes thermal ionization in the shock layer
- Numerous free electrons that can be influenced by magnetic fields
- Sustained electron motion constitutes an electric current
- MHD generator converts vehicle kinetic energy otherwise lost as heat into useful electrical energy
- Termed 'regenerative aerobraking'



Sample Power and Velocity Profile for a 7.5 km/s Direct Entry at Mars[3]

Theory and Methodology

Calculating Power Available through MHD Energy Generation

- Power available through MHD energy generation scales as follows:

$$P \propto n_e u^2 B^2 A_c L_i$$

- Vehicle velocity determined by following equations of motion:

$$\ddot{\bar{r}} = -\frac{\mu_{Mars}}{(\bar{r}\cdot\bar{r})^{3/2}}\bar{r} - \frac{\rho(\dot{\bar{r}}\cdot\dot{\bar{r}})}{2\beta}\hat{\dot{\bar{r}}}$$

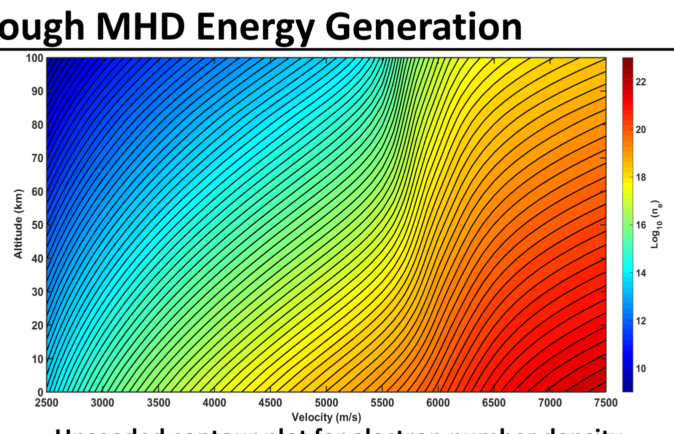
- Where β is the ballistic coefficient:

$$\beta = \frac{m}{C_D A}$$

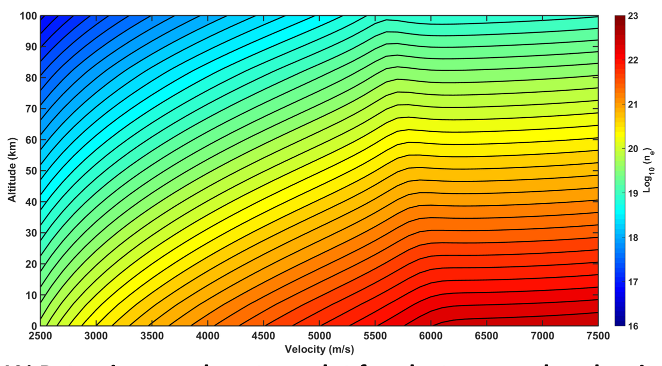
- Electron number density determined by solving 1-d shock with NASA Chemical Equilibrium with Applications code
- Requires velocity, ambient atmospheric conditions, and atmospheric composition

Constituent	Relative Abundance
CO_2	96.0%
Ar	1.9%
N_2	1.9%
O_2	0.14%
CO	0.06%

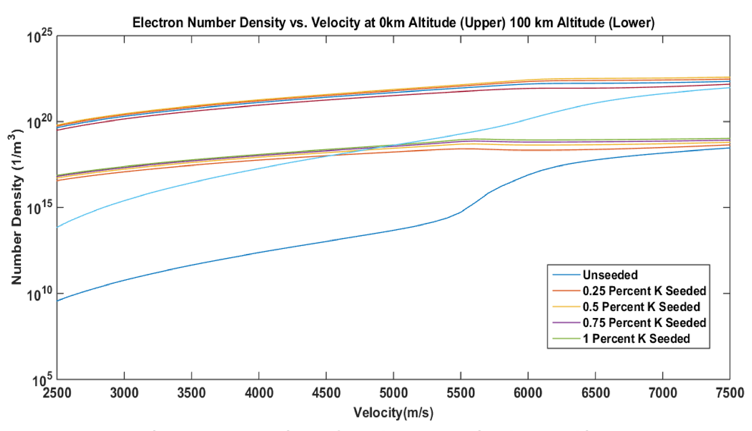
Martian atmospheric composition



Unseeded contour plot for electron number density

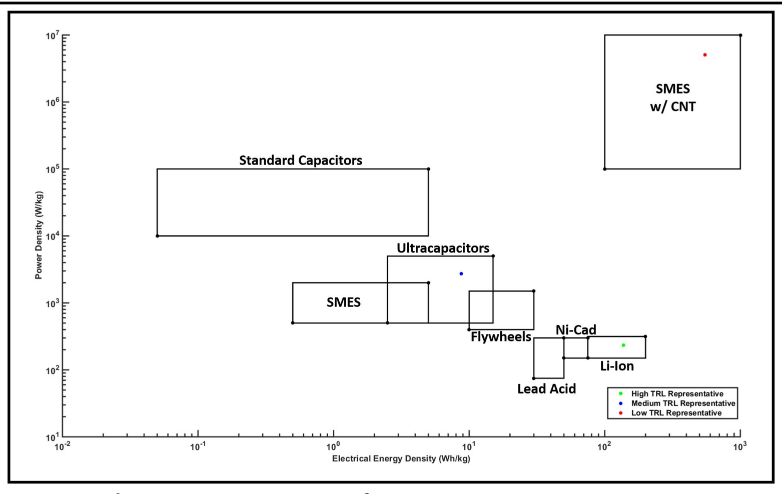


1% Potassium seed contour plot for electron number density

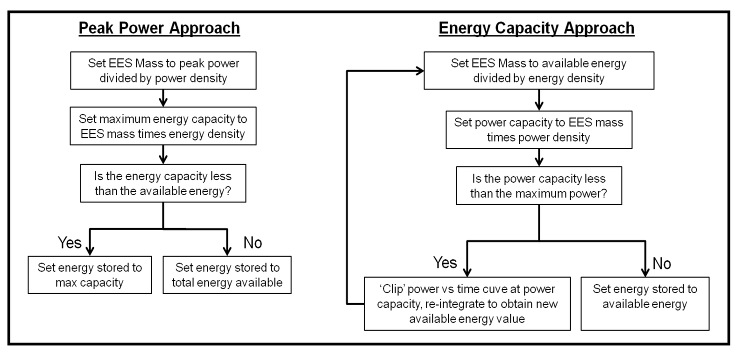


Electron number density vs. velocity at 0km (upper) and 100km (lower) altitudes

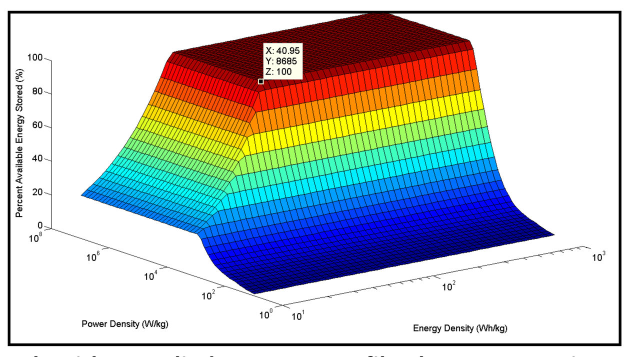
Electrical Energy Storage (EES) Systems Performance Modeling



Abstract EES system performance to two parameters: specific energy and specific power



Algorithm for calculating EES system mass



Algorithm applied to power profile above over entire parameter space for EES systems, limited to 100kg mass. Cursor shows minimum EES performance required

Vehicle Configurations, Initial Conditions, and Parameter Study

Vehicle	Mass (kg)	C_D	A (m^2)	β (kg/m^2)
Mars Pathfinder	582	1.68	5.52	63.1
Mars Science Lab	3151	1.68	16.6	112.9
Moses Test Vehicle[4]	1000	0.4	7.00	357.1
Mars Human Mission	100,000	1.68	78.5	757.9

Vehicle configurations under consideration

5km/s Initial Velocity Multi Pass	Mars Pathfinder		Mars Science Lab		Moses Test Vehicle		Mars Human Mission	
	γ_{entry}(º)	Time in Atm(s)	γ_{entry}(º)	Time in Atm(s)	γ_{entry}(º)	Time in Atm(s)	γ_{entry}(º)	Time in Atm(s)
2	-3.50	751	-4.20	1260	-5.50	1356	-6.35	1459
4	-2.05	1081	-3.05	1320	-4.65	2027	-5.65	2276
6	-1.40	1180	-2.35	1496	-4.05	2566	-5.20	2953
8	-1.00	1261	-1.75	1680	-3.60	2977	-4.80	3589
10	-0.85	1270	-1.45	1805	-3.20	3335	-4.50	4146

Vehicle	7 km/s Direct Entry		5km/s Direct Entry	
	γ_{entry}(º)	Time in Atm(s)	γ_{entry}(º)	Time in Atm(s)
Mars Pathfinder	-11.00	242	-11.00	240
Mars Science Lab	-11.00	223	-11.00	215
Moses Test Vehicle	-11.00	204	-11.00	175
Mars Human Mission	-11.00	215	-11.00	159

Simulation initial conditions at 100km for trajectories studied

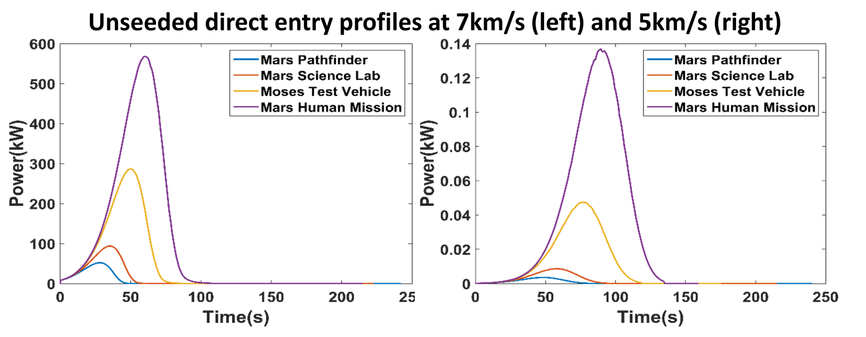
Seeding Levels (% Mass K)	Vehicle Configurations	Trajectory Types	EES Mass Constraint, %M Vehicle
Unseeded	Mars Pathfinder	7km/s Direct	5%
0.25%	Mars Science Lab	5km/s Direct	10%
0.50%	Moses Test Vehicle	5km/s 2 Pass	15%
0.75%	Mars Human Mission	5km/s 4 Pass	20%
1.00%		5km/s 6 Pass	25%
		5km/s 8 Pass	
		5km/s 10 Pass	

Parameter study summary

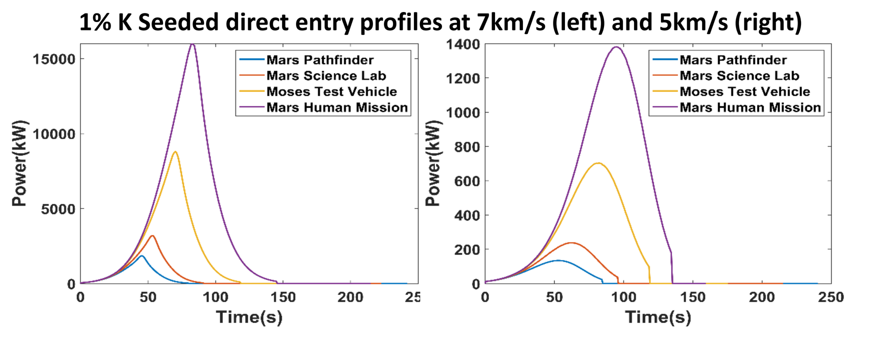
Results and Discussion

Direct Entry Power Profiles

Unseeded direct entry profiles at 7km/s (left) and 5km/s (right)



1% K Seeded direct entry profiles at 7km/s (left) and 5km/s (right)



Peak power and total available energy both increase with increasing vehicle ballistic coefficient. In addition, power available for MHD energy generation is much higher with an entry velocity increase from 5km/s to 7km/s

Peak Power and Energy Available for Each Configuration

7km/s Direct Entry Peak Power and Total Energy Available

Vehicle	Mars Pathfinder		Mars Science Lab		Moses Test Vehicle		Mars Human Mission	
Potassium Seeding Level	Total Energy Available (MJ/m^2)	Peak Power (kW/m^2)	Total Energy Available (MJ/m^2)	Peak Power (kW/m^2)	Total Energy Available (MJ/m^2)	Peak Power (kW/m^2)	Total Energy Available (MJ/m^2)	Peak Power (kW/m^2)
Unseeded	1.36	52.24	2.65	93.77	9.44	287.26	20.93	568.30
0.25%	15.54	528.44	29.04	916.98	96.94	2524.83	209.12	4585.37
0.50%	27.48	987.19	51.35	1711.76	171.16	4709.60	368.68	8614.05
0.75%	38.63	1428.22	72.19	2476.71	240.45	6792.40	517.43	12359.46
1.0%	49.29	1853.51	92.13	3205.28	306.64	8803.19	659.30	15989.27
$R_{1\%/Unseeded}$	36.22	35.48	34.71	34.18	32.48	30.65	31.50	28.14

5km/s Direct and Multi-Pass Entry Peak Power and Total Energy Available, 1% K Seeded

Vehicle	Mars Pathfinder		Mars Science Lab		Moses Test Vehicle		Mars Human Mission	
Number of Passes	Total Energy Available (MJ/m^2)	Peak Power (kW/m^2)	Total Energy Available (MJ/m^2)	Peak Power (kW/m^2)	Total Energy Available (MJ/m^2)	Peak Power (kW/m^2)	Total Energy Available (MJ/m^2)	Peak Power (kW/m^2)
Direct	6.38	134.41	11.76	237.95	37.59	703.54	78.17	1381.41
2	4.47	21.50	8.97	36.11	34.64	106.57	79.07	237.58
4	3.39	13.74	7.37	21.05	31.21	61.10	74.85	138.61
6	3.06	12.38	6.45	16.30	28.42	42.36	71.27	98.80
8	2.89	12.00	5.82	13.86	26.16	32.52	67.81	74.12
10	2.84	11.94	5.56	13.05	24.27	26.27	64.93	60.41
$R_{direct/10Pass}$	2.25	11.25	2.12	18.23	1.55	26.78	1.20	22.87

For the 7km/s entries, seeding has a large effect, but scales peak power and total available energy similarly. For the 5km/s entries, Peak power and total available energy available energy both decrease as the number of passes is increased. However, peak power drops much more significantly than total available energy.

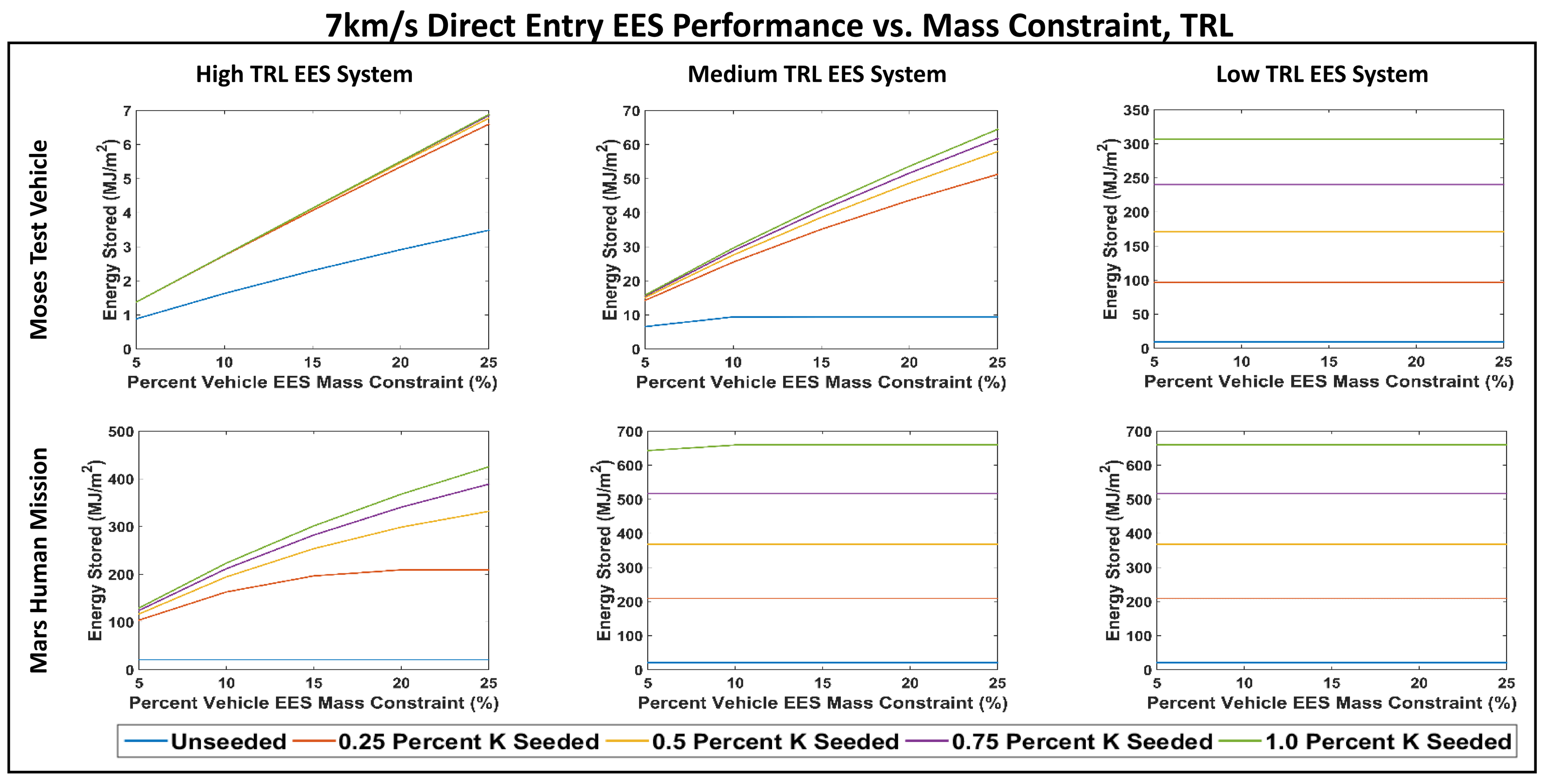
Minimum EES System Performance at 1% K Seed and 5% Mass Constraint

Vehicle	Mars Pathfinder		Mars Science Lab		Moses Test Vehicle		Mars Human Mission	
Trajectory	Min Specific Energy (Wh/kg)	Min Specific Power (W/kg)	Min Specific Energy (Wh/kg)	Min Specific Power (W/kg)	Min Specific Energy (Wh/kg)	Min Specific Power (W/kg)	Min Specific Energy (Wh/kg)	Min Specific Power (W/kg)
7 km/s Direct	498	70548	163	23101	1831	187382	37	3275
5 km/s Direct	64	4977	21	1630	215	15199	<10	305
5 km/s 2 Pass	44	811	16	231	196	2154	<10	<100
5 km/s 4 Pass	34	534	13	152	179	1233	<10	<100
5 km/s 6 Pass	31	464	12	115	163	933	<10	<100
5 km/s 8 Pass	28	464	11	<100	148	705	<10	<100
5 km/s 10 Pass	28	464	<10	<100	135	534	<10	<100

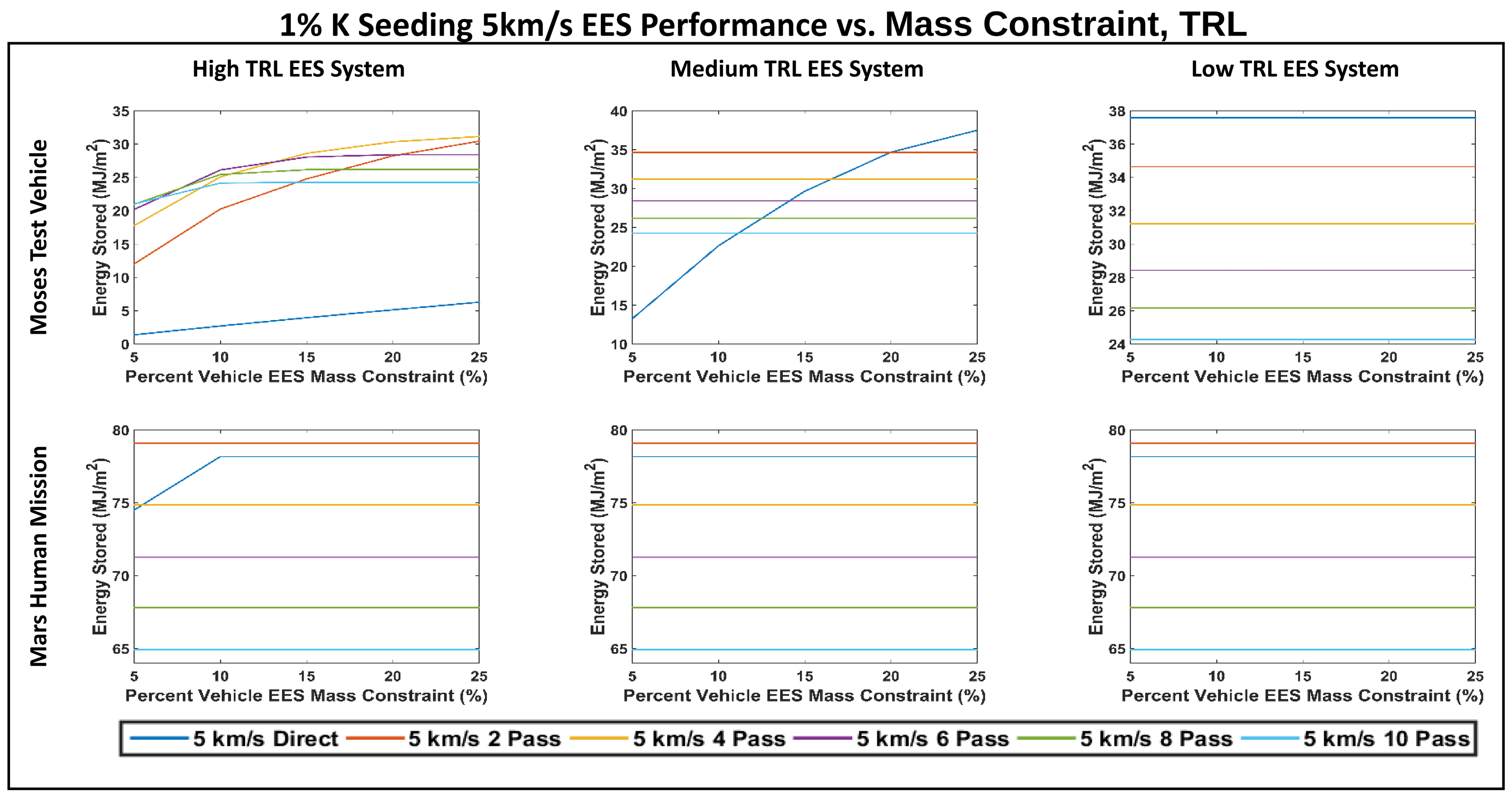
For the 7km/s entry velocity, the minimum EES system requirements are much higher than the 5km/s case owing to the higher available power and energy. For the 5km/s entry velocity, the principal effect of multi-pass trajectories is to reduce the minimum EES specific power required.

EES System Performance vs. Technology Readiness Level (TRL) and Mass Constraint

7km/s Direct Entry EES Performance vs. Mass Constraint, TRL



1% K Seeding 5km/s EES Performance vs. Mass Constraint, TRL



The Moses test vehicle is the most dependent on mass constraint for the EES system owing to it's high ballistic coefficient and low vehicle mass, while the Mars Human mission vehicle is the least owing to it's much higher vehicle mass. For the 7km/s direct entry, only the low TRL EES system had no dependence on mass constraint . For the 5km/s entry cases, the Mars Human mission vehicle has no dependence with a 10% mass constraint or above for all EES TRLs, while the MOSES test vehicle requires a low TRL EES system for no dependence on mass constraint.

Conclusions

- Available power and energy go up with increasing ballistic coefficient
- Low TRL EES technologies required for lower mass missions
- Lowest performance requirement for EES technology achieved with low ballistic coefficient, high mass sytems
- 100% available energy storage possible for Mars Human class mission vehicle

References

[1] Braun, R.D.; Manning, R.M., "Mars exploration entry, descent and landing challenges," *Aerospace Conference, 2006 IEEE* , 4-11 March 2006. [2]Spencer, D., Blanchard, R., Braun, R., Pathfinder Entry, Descent, and Landing Reconstruction," *Journal of Rockets*, Vol. 36, No. 3, May-June 1999. [3]Moses, R.W., Kuhl, CA., and Templeton, J.D., "Plasma Assisted ISRU at Mars," *15th International conference on MHD Energy Conversion,* Moscow, Russia, 24-27 May 2005.

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